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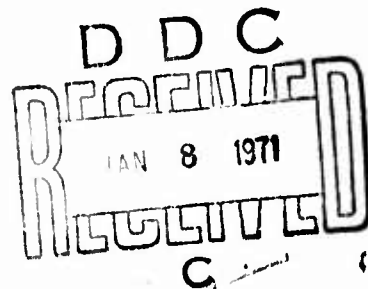
MEMORANDUM REPORT NO. 2074

SHOCK-INDUCED ELECTRICAL SIGNALS WITH POSITIVE AND NEGATIVE COMPONENTS

by

G. E. Hauver

November 1970



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BALLISTIC RESEARCH LABORATORIES

MEMORANDUM REPORT NO. 2074

NOVEMBER 1970

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WITH POSITIVE AND NEGATIVE COMPONENTS**

G. E. Hauver

Terminal Ballistics Laboratory

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ABERDEEN PROVING GROUND, MARYLAND

BALLISTIC RESEARCH LABORATORIES

MEMORANDUM REPORT NO. 2074

G. E. Hauver
Aberdeen Proving Ground, Md.
November 1970

SHOCK-INDUCED ELECTRICAL SIGNALS
WITH POSITIVE AND NEGATIVE COMPONENTS

ABSTRACT

Shock-induced electrical signals from polyethylene have been examined within the framework of the Allison polarization theory, and have been found to consist of both positive and negative components. The similarity to certain shock-induced electrical signals from alkali halide crystals is noted, and hypothetical signals have been calculated to display the basic features of a few alkali halide signals selected from the literature. The calculations suggest that signal profiles may not provide a clear indication of shock-wave transit time when both positive and negative components are present.

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LIST OF SYMBOLS

I	current
I_0	initial value of the current
Q	electric charge on the electrodes
Q^*	electric charge on the electrodes at time t^*
U	shock velocity
x_0	initial thickness of the dielectric
k	dielectric constant of shock-compressed dielectric
k_0	dielectric constant of unshocked dielectric
t	time
t^*	time of shock arrival at the second electrode
u	particle velocity
τ	relaxation time

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I. INTRODUCTION

Shock-induced electrical signals (polarization signals) from dielectrics are commonly investigated using the configuration of a parallel-plate capacitor in which a plane shock wave enters the dielectric at normal incidence from one electrode. In an idealized experiment, the signal would be studied in the absence of any perturbing influence on the polarizing shock wave. The idealized experiment has been approached in tests with polyethylene by using a flat pressure-time profile and a guard-electrode configuration formed from a vapor-deposited metal film contained within the dielectric. This arrangement minimizes the influence of pressure relief at the lateral boundary and mismatch between the shock impedances of the dielectric and electrode metal. The recorded signal in such an experiment consists of the shock-induced polarization signal followed by the relaxation signal (relaxation portion of the observed signal) which occurs after the shock front arrives at the second electrode. The Allison polarization theory^{(1)(*)} has been used to analyze a shock-induced electrical signal from polyethylene, and has revealed that it consists of positive and negative components. Mineev, et.al⁽²⁾ and Wong, Linde, and White⁽³⁾ have suggested the presence of positive and negative components in polarization signals from alkali halide crystals, although signals were not analyzed. Some characteristics of signals with positive and negative components have become evident from resolving the components of polyethylene signals. Since the nature of positive and negative components in alkali halide signals has not been reported, the Allison theory was used to calculate simple hypothetical signals that display the basic profile features of a few alkali halide signals selected from the literature.

(*) References are found on page 30 .

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Polarization signals are sometimes used to establish shock-wave transit times, from which shock velocity may be calculated⁽⁴⁾. The studies of signals with positive and negative components have revealed that the times at which a shock front enters and emerges from a dielectric specimen may not be clearly evident from features of the signal profile.

This report briefly summarizes the theory used in polarization calculations; presents the analysis of a shock-induced electrical signal from polyethylene at 47 kbar; includes hypothetical signals which exhibit the basic features of several alkali halide polarization signals, and cites instances in which electrical signals with both positive and negative components might lead to an erroneous measurement of shock-wave transit time through a dielectric specimen.

II. POLARIZATION THEORY

The Allison theory of shock-induced polarization assumes that polarization is induced at the shock front and then decays with a characteristic relaxation time τ . If the RC time constant of the circuit is much less than the shock-wave transit time (RC is commonly one nanosecond or less), the load may be considered effectively a short circuit, and displacement current is given by the expression (symbols are defined in the List of Symbols on page 9),

$$I = \left[C_1 Q + I_0 X_0 \exp(-t/\tau) \right] / (X_0 - C_1 t),$$

where,

$$Q = Q^* t^* I_0 X_0 \tau \left[1 - \exp(-t/\tau) \right] / (C_2 t + Q^* t^* X_0),$$

$$C_1 = U - (k_0/k) (U - u),$$

$$C_2 = I_0 X_0 \tau \left[1 - \exp(-t^*/\tau) \right] - Q^* t^* U,$$

and,

$$I_0 = Q^* k_0 (U - u) / \tau k U \left[1 - \exp(-t^*/\tau) \right].$$

If polarization is induced only in the vicinity of the shock front, then no additional polarization is induced in the inter-electrode volume after the shock front arrives at the second electrode. This assumes that the shock impedance of the electrode is the same as that of the dielectric, so that neither a shock nor rarefaction reflect into the dielectric from the interface. It then follows from the Allison theory that the charge Q^* , which is on the electrodes at time t^* , decays with the characteristic relaxation time τ . The current in the relaxation signal, which occurs after the shock front arrives at the second electrode, is given by the expression,

$$I = (-Q^*/\tau) \exp \left[- (t - t^*)/\tau \right],$$

where $t \geq t^*$.

For the special case of nonrelaxing polarization, Allison's treatment is followed after making the initial assumption that the polarization induced at the shock front remains constant within the shock compressed portion of the dielectric. The displacement current is then given by the expression,

$$I = \left[Q^* (k_0/k) (U - u) X_0 \right] / (X_0 - C_1 t)^2,$$

where,

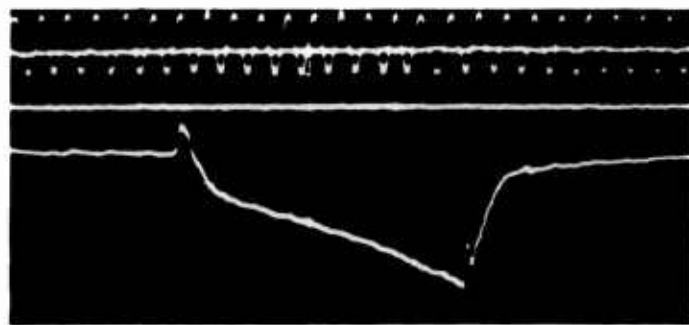
$$C_1 = U - (k_0/k) (U - u).$$

In this special case, there is no relaxation signal.

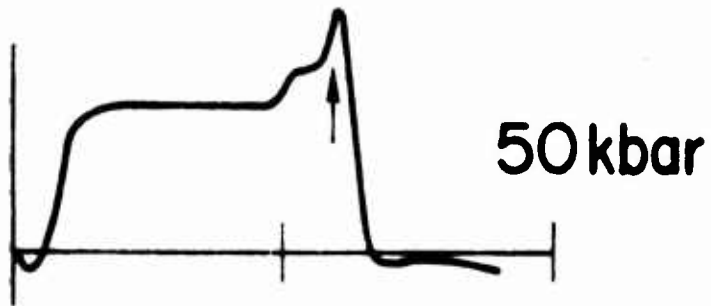
Risetime is an essential feature of shock-induced electrical signals. When specimen diameters are reduced to a few millimeters, signal risetimes frequently approach the limitations imposed by wideband (150 MHz and greater) oscilloscopes. However, specimen dimensions are usually larger than a few millimeters, and for explosively produced shock waves, the risetime is commonly found to be limited by the time interval during which the incident shock front enters the dielectric. Although it is conceded that long risetimes may sometimes be inherent in the polarization mechanism, for the calculations of this report it has been assumed that the risetime results from a plane but obliquely incident shock front. Over the circular area of the dielectric specimen, the shock front has been linearly subdivided into stepped elemental areas which are assumed to be parallel with the electrode-dielectric interface. Twenty elements, for example, were used to analyze the shock-induced electrical signal from polyethylene. The elemental contributions to the displacement current are summed at selected times after the shock front first encounters the interelectrode dielectric.

III. SHOCK-INDUCED ELECTRICAL SIGNAL FROM POLYETHYLENE

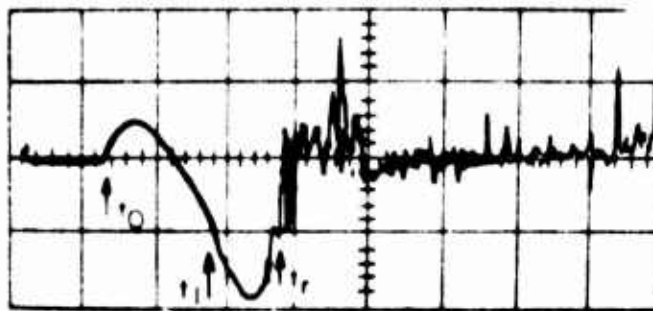
Polyethylene, like many dielectric materials, produces an electrical signal during shock compression. The experimental arrangement used to observe polyethylene signals was similar to the guard-electrode configuration used in polarization studies of Plexiglas and polystyrene⁽⁴⁾. However, in tests with polyethylene, the vacuum deposited second electrode and its guard were backed with additional polyethylene. This arrangement was used to prevent the shock wave from being perturbed at the second electrode, making it possible to study the relaxation signal. The polyethylene assembly was built onto a coaxial connector, and the coaxial test configuration was mounted on a flat metal plate which served as the first electrode. A plane shock wave, transmitted through the first electrode, produced the shock-induced electrical signal shown in Figure 1-A. The signal was observed as the voltage drop across the terminating resistor of the coaxial cable that connected the test assembly to the oscilloscope. Time increases from left to right and may be gauged by the 50 MHz sine wave at the top. The signal begins with a positive rise that occurs when the shock wave enters the dielectric. The risetime is approximately six nanoseconds, which implies that the incident shock front was inclined two milliradians from the plane of the electrode-dielectric interface. Features of the signal profile which need to be explained are the positive portion at the beginning, the slow rise of the negative portion, the jog that occurs near the time of shock arrival at the second electrode, and the later slow decay of the relaxation signal back toward zero. In order to analyze the signal within the framework of the Allison theory, it is necessary to have information about the relaxation, the Hugoniot, and the dielectric constant of shock-compressed polyethylene. Information about relaxation was obtained by analyzing the profile of the relaxation signal. (This analysis consisted of distributing the charge Q^* among the minimum number of relaxing components necessary to describe the relaxation signal.) The Hugoniot and dielectric constant for the high-density



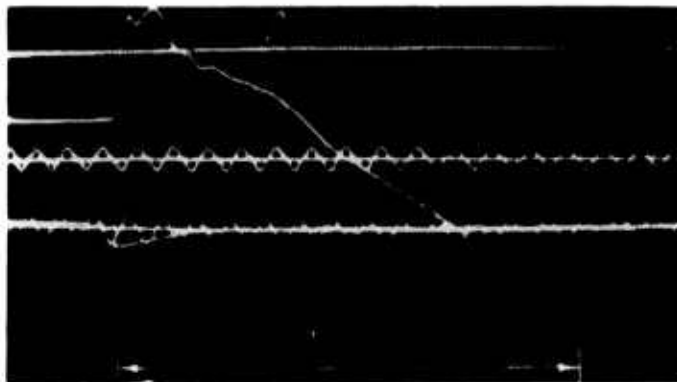
A



B



C



D

Figure 1. Shock-induced electrical signals with positive and negative components.

polyethylene ($\rho_0 = 0.960$ g/cc) used in this test have been measured and reported⁽⁵⁾.

The results of the signal analysis are shown in Figure 2. They indicate that the observed signal was composed of three components, one negative and two positive. Polarization induced at the shock front (P_S^0), and relaxation time (τ), are listed in Table 1. The three components were added algebraically to obtain the circular points in Figure 2. The circular points show reasonable agreement

Table I. Components of the Shock-Induced Electrical Signal from Polyethylene at 47 kbar.

Component	$P_S^0 - \mu\text{C}/\text{m}^2$	$\tau - \mu \text{ sec}$
S_1	-0.3175	2.6
S_2	+0.1272	0.24
S_3	+0.3694	0.014

with the solid curve, which represents the observed signal. The greatest departure of the calculated signal from the observed signal occurs just after the shock front arrives at the second electrode, where the calculation yields a relaxation peak which lies approximately below the jog in the signal. This tends to pull the calculated signal below the observed signal for approximately 30 to 40 nanoseconds. This discrepancy has not yet been completely resolved. It may indicate that the shock wave is perturbed measurably at the second electrode. However, in this test, the metal of the vapor deposited second electrode was inadvertently made different from the metal of the lead wire, setting up a bi-metallic junction. Therefore, it is more strongly suspected that a thermoelectric signal occurred, temporarily distorting the relaxation signal which has a maximum amplitude in the order of only ten millivolts.

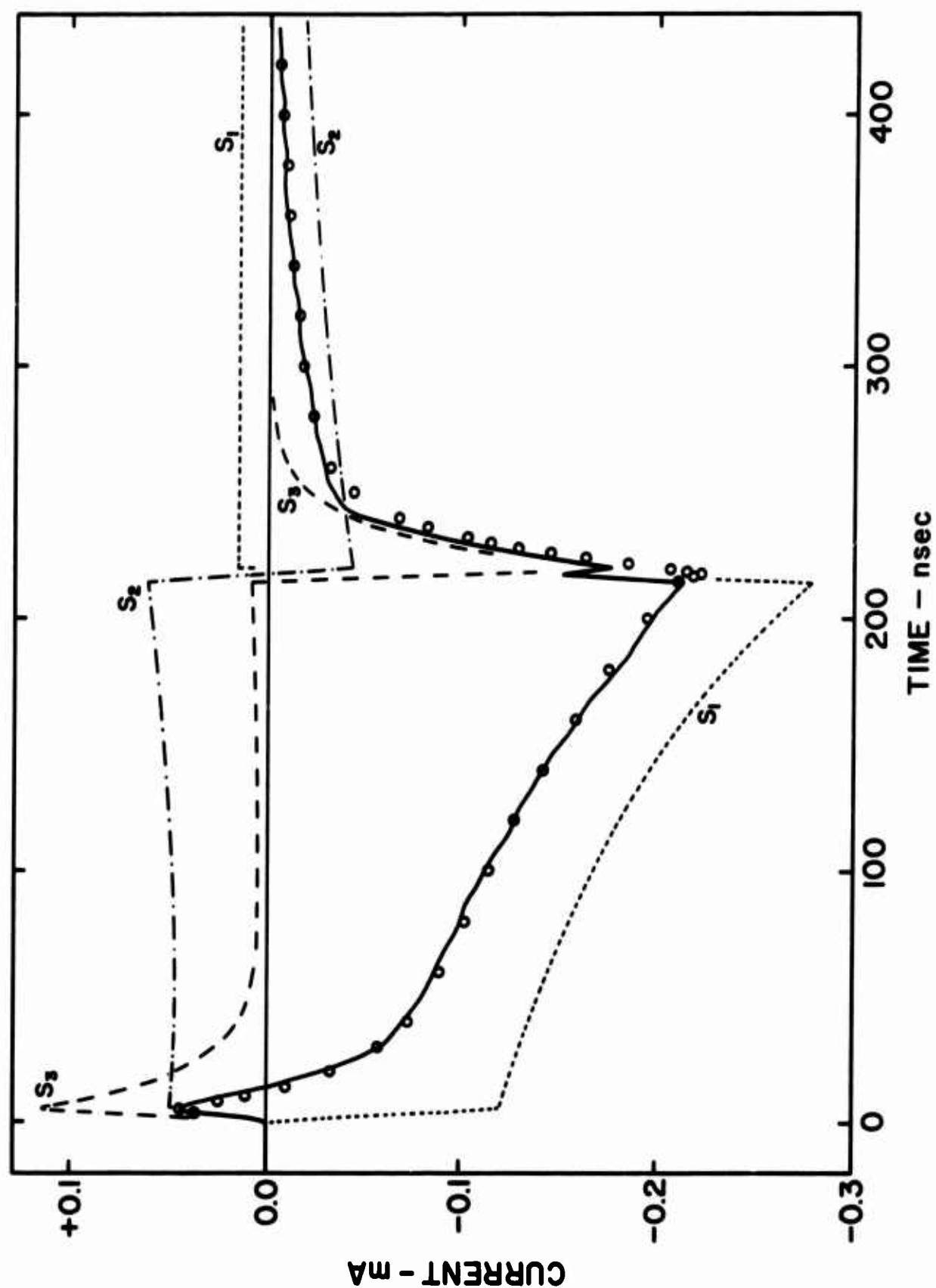


Figure 2. Resolution of a 47 kbar polyethylene signal into positive and negative components.

It is evident that the positive component S_3 is primarily responsible for the positive portion at the beginning of the signal, and for the slow rise of the negative portion. The slow decay of the relaxation signal back toward zero is the result of the relative relaxations of components S_1 and S_2 , and if the signal could have been observed at later times (while delaying pressure relief), the relaxation current would have crossed to positive values before finally going to zero. This signal, at 47 kbar, is in the pressure range where a polarity change occurs. At lower pressures, the negative component S_1 predominates. At higher pressures, the positive components predominate and the observed polarization signal is entirely positive, although the relaxation signal still reveals the presence of the negative component.

In principle, the shock-induced polarizations and the relaxation times can be obtained by considering only the relaxation signal, the measured dielectric constant, and the Hugoniot. Calculating the profile of the polarization signal may seem to be excess effort. However, in practice, the relaxation signal only provides the number of components and close first estimates of each relaxation time τ and each initial relaxing charge Q^* . The values are refined by working back and forth between the two portions of the observed signal.

IV. HYPOTHETICAL SIGNALS

Similarities between shock-induced electrical signals from polyethylene and the alkali halides have been noticed. Polyethylene signals undergo a polarity change from negative to positive when test pressures are increased through the range from 15 to 170 kbar. The signals from certain alkali halide crystals undergo similar polarity changes. The shock-induced polarization signal from the (111) orientation of sodium chloride, for example, is positive at low pressures, becomes negative in the vicinity of 100 kbar, and reverts back to positive polarity near 200 kbar, which corresponds

closely to the pressure of the transition from NaCl to CsCl structure which was indicated by lateral relaxation measurements⁽⁶⁾. Alkali halide signals, like polyethylene signals, sometimes exhibit polarity changes while the shock wave is traveling through the dielectric. Such signals are shown in Figure 1-B, C, and D. Signal B was reported by Wong, Linde, and White⁽³⁾ for calcium-doped (100) NaCl. The authors also reported that signals from pure NaCl sometimes began with such a dip of reversed polarity. Signal C is a related signal from NaCl, reported by Linde, Murri, and Doran⁽⁷⁾; and signal D is a similar signal from KBr, reported by Mineev, et.al.⁽²⁾.

References [2] and [3] suggest that alkali halide signals contain positive and negative components. This suggestion is supported by the similarity to polyethylene signals. The alkali halide signals were not resolved into components; and therefore, some simple hypothetical signals have been calculated to suggest the nature of components required to produce the basic features of the signals shown in Figure 1. A nonrelaxing negative component and a relaxing positive component were chosen, and it was assumed that,

$$U/(U - u) = k/k_0 = 1.2.$$

The assumption $k > k_0$ may seem questionable. Static measurements by Samara and Chrisman⁽⁸⁾ show that the dielectric constants of single-crystal NaCl, KCl, and RbCl decrease monotonically with increasing pressure. The dielectric constants of KCl and RbCl undergo a step increase at the phase transition from NaCl to CsCl structure, after which the decreasing trend resumes. The dielectric constant of NaCl decreases up to the maximum test pressure of 26 kbar, and the decreasing trend might be expected to continue since NaCl shows no evidence of transforming to the CsCl structure below 200 kbar. However, it is very difficult to reconcile the assumption $k_0 > k$ with the profiles of the less complex alkali

halide polarization signals such as those from (111) NaCl observed in the pressure range from 125 to 150 kbar. Using the (111) NaCl polarization signals as a guide, $k > k_0$ was assumed, and the value 1.2 was somewhat arbitrarily chosen. In calculating hypothetical signals, it was also assumed that the second electrode was matched to the shock impedance of the dielectric, and that the shock front was plane but obliquely incident. The transit time for the shock wave was normalized to 1.0, and risetimes of either 0.10 or 0.05 were introduced.

Figure 3 shows a two component signal that was calculated to display the basic features of the polyethylene signal (Signal A in Figure 1, and fully resolved in Figure 2). The broken curves represent the components, and the solid curve represents the algebraic addition. This signal served as a starting point for the other calculated signals. The magnitude of the negative component was decreased slightly to obtain the signal shown in Figure 4. Here, the initial positive portion and the rounded rise of the negative portion are essentially unchanged, but relaxation of the positive component carries the observed signal further negative just after shock arrival at the second electrode. This signal is believed to display the basic features of Signal B in Figure 1, although polarities are reversed. Signal B returns nearly to zero (like the calculated signal) because the second electrode was magnesium which closely matches the shock impedance of NaCl. The relaxation time of the positive component was increased and the component magnitudes were adjusted slightly to obtain the signal shown in Figure 5. Here, the solid curve resembles Signals C and D in Figure 1. Signal C [10 kbar, (100) NaCl, Ref. 7] exhibits a much longer risetime than the calculated signal. This tends to smooth the signal at the time of shock arrival at the second electrode (time t_1 in Figure 1-C). After time t_1 , the signal deflects

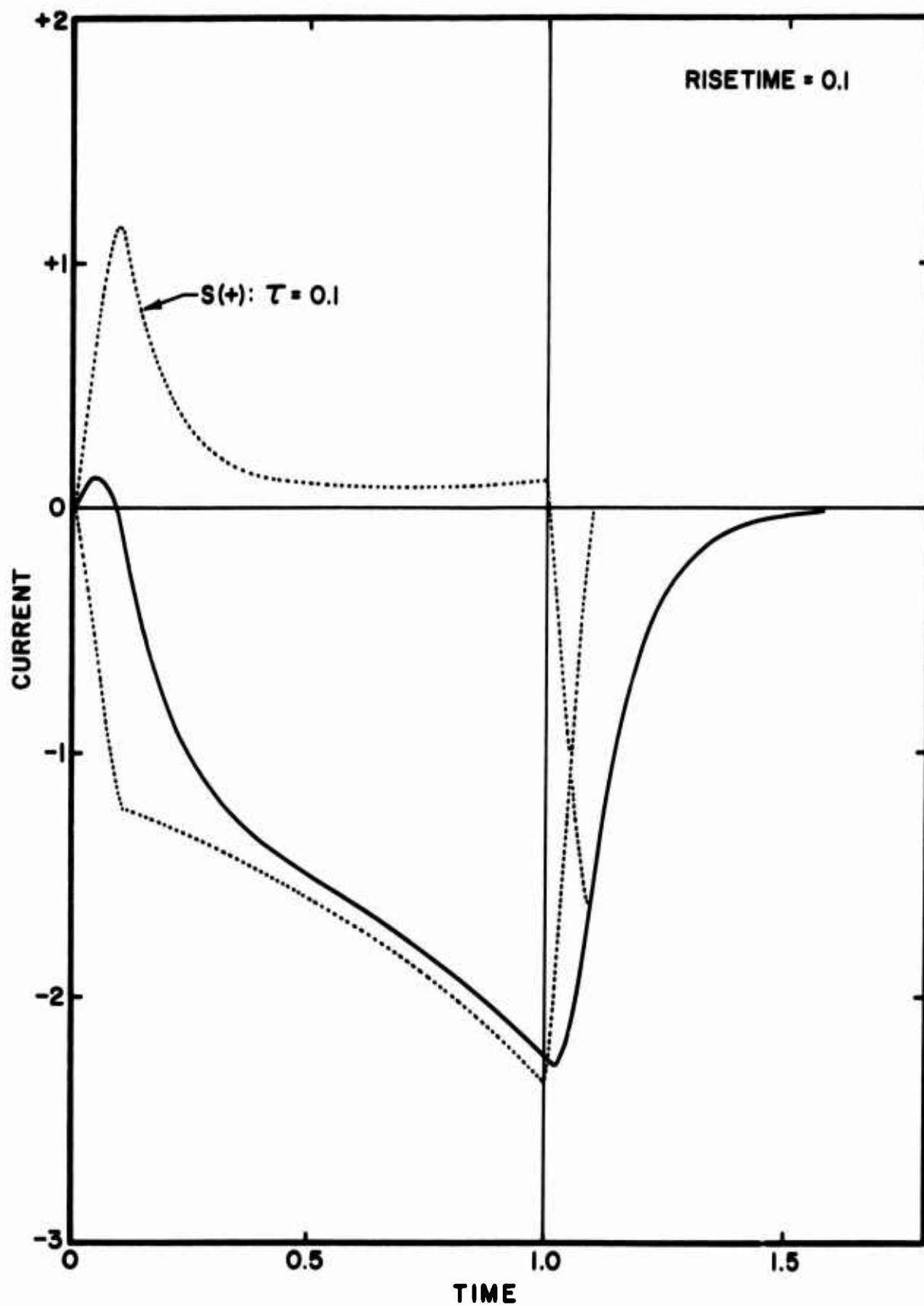


Figure 3. Two-component signal calculated to display the basic features of Signal A in Figure 1.

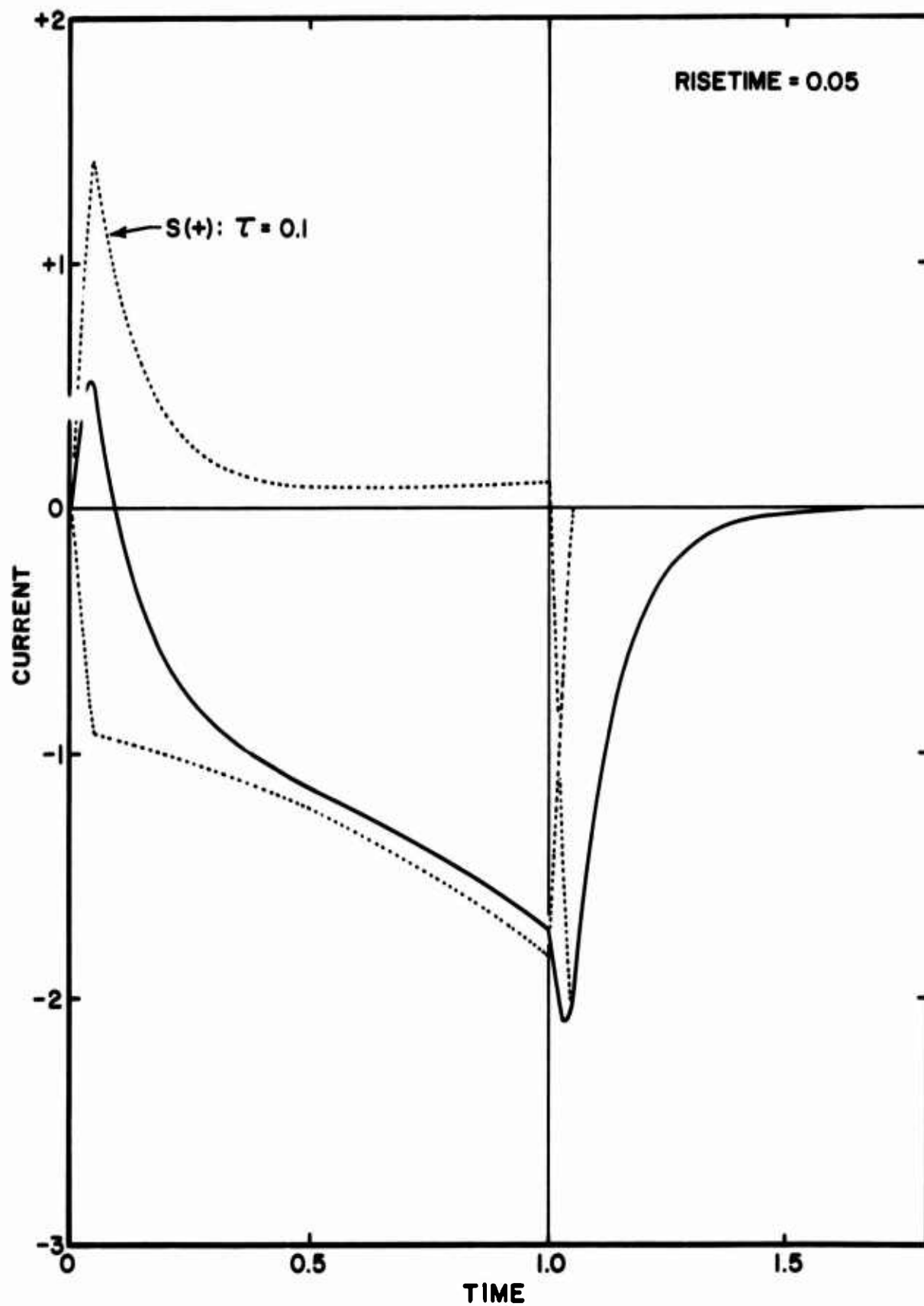


Figure 4. Two-component signal calculated to display the basic features of Signal B in Figure 1.

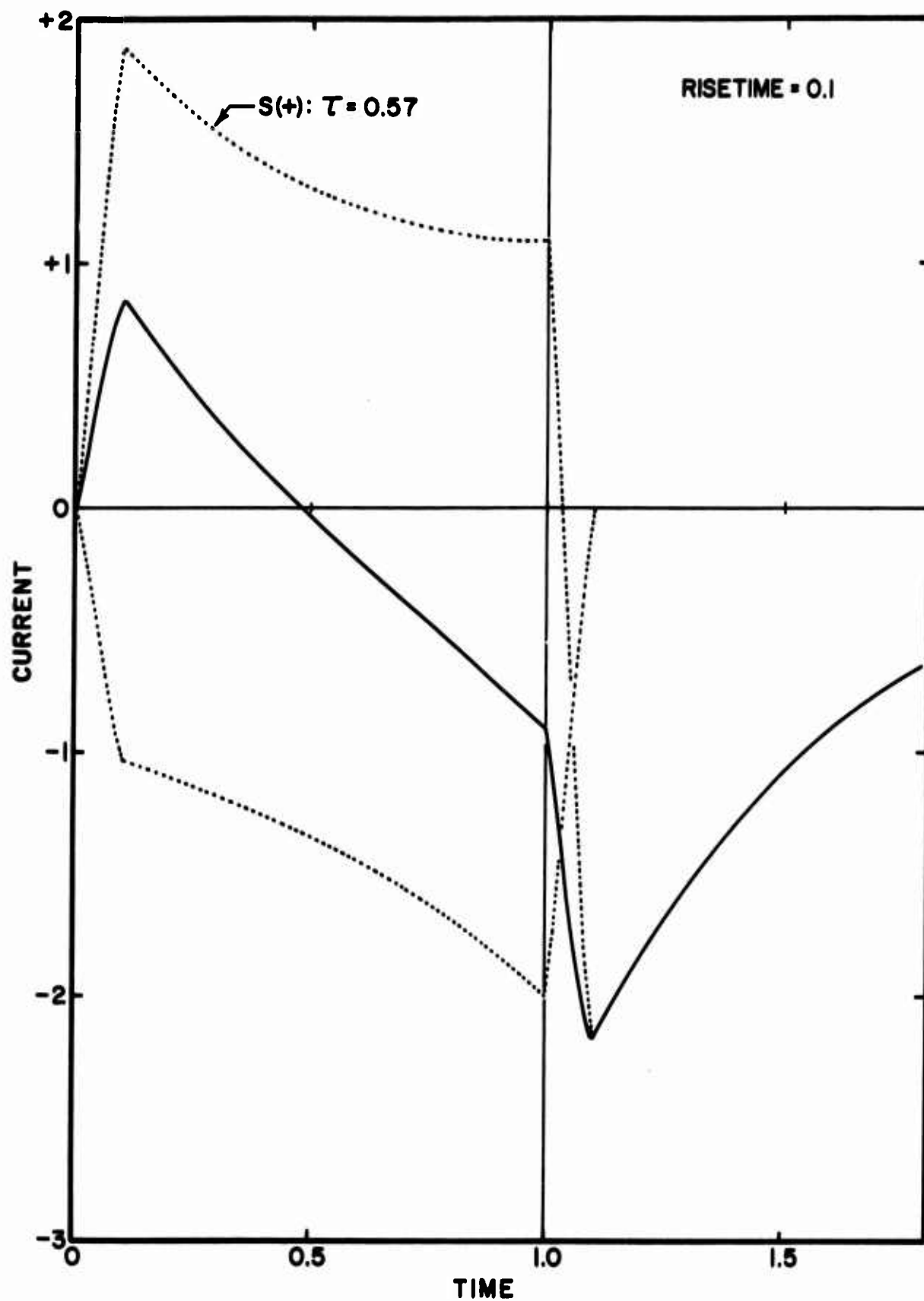


Figure 5. Two-component signal calculated to display the basic features of Signals C and D in Figure 1.

further negative during an additional interval which approximately equals the risetime, and then returns to zero. Again, it should be noted that a magnesium electrode was used. Signal D (78 kbar, KBr, Ref. 2) closely resembles the calculated signal in Figure 5. However, Signal D deflects in the positive direction when the shock wave arrives at the second electrode. This undoubtedly resulted from an impedance mismatch at the second electrode.

The similarity between the hypothetical signals and the selected alkali halide signals (especially signals C and D) supports the coexistence of positive and negative components at certain pressures. However, the assumption of one positive and one negative component is undoubtedly an oversimplification, and Figure 6 is offered as evidence of greater complexity. Figure 6 shows a signal from a nominally pure optical single crystal of (111) NaCl at 180 kbar. Unfortunately, the second electrode was not matched to the shock impedance of NaCl. The signal is shown terminated at the time of shock arrival at the second electrode, and an analysis was not attempted. However, a superficial inspection of the profile suggests the presence of two and perhaps three negative contributions to the signal, and since the signal size is decreasing for the change to positive polarity near 200 kbar, at least one positive component is also suspected.

V. TRANSIT - TIME MEASUREMENTS

Shock-induced electrical signals are sometimes used to determine shock-wave transit times through dielectric specimens⁽⁴⁾. For many dielectrics, features of the signal profile provide a measure of the transit time that compares within experimental error with the transit time obtained by other electrical or optical techniques. However, if the signal contains components of both polarities, the times of shock entry and emergence may not be well defined by features of the signal profile. In Figure 3, for example, the shock

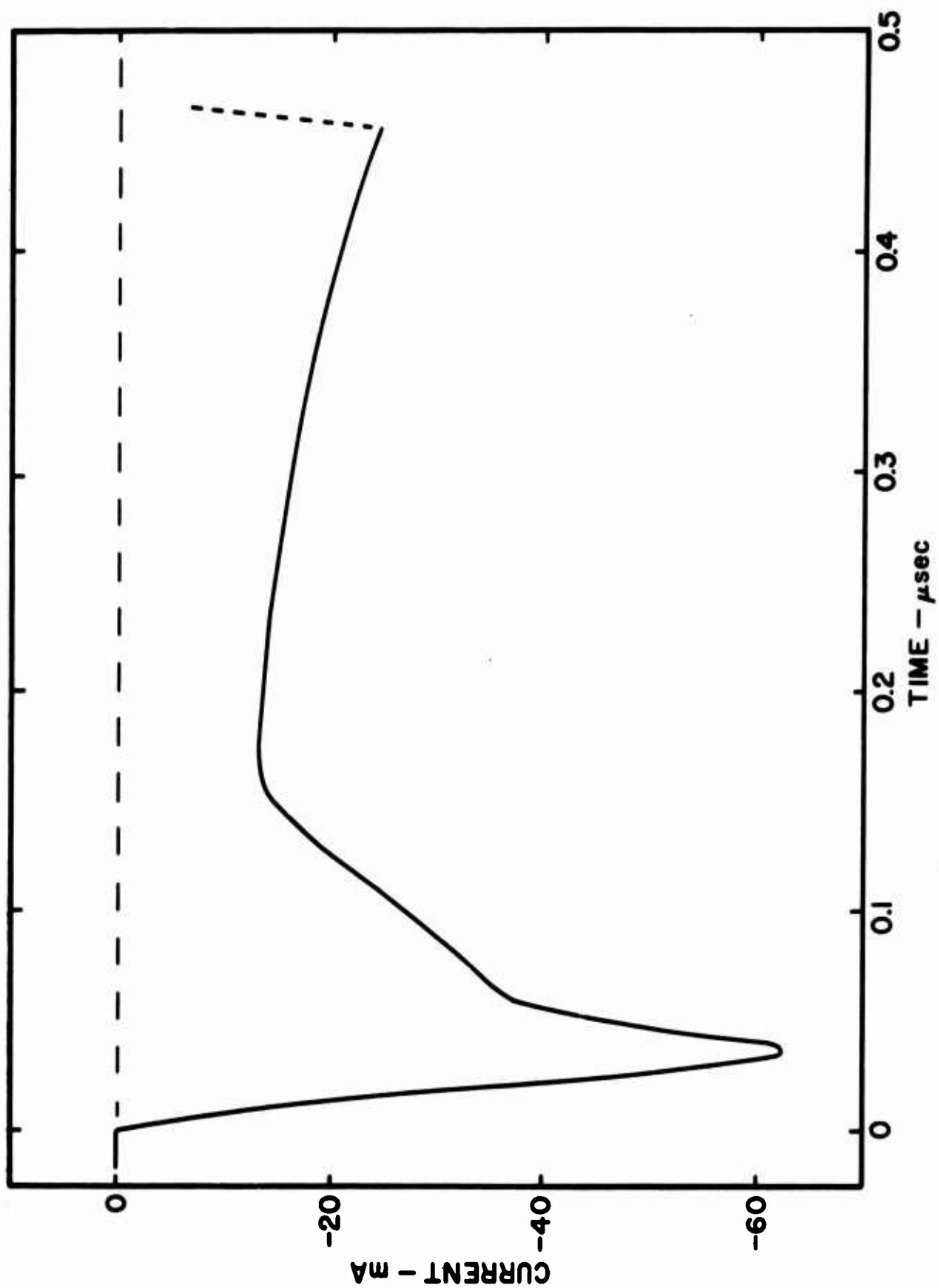


Figure 6. Shock-induced electrical signal from (111)
NaCl at 180 kbar.

reaches the second electrode at time 1.00, although the observed signal is supported during the risetime of the relaxation signal from the positive component, and does not deflect toward zero until time 1.02. The observed signal in Figure 1-A is believed to deflect toward zero upon shock arrival at the second electrode, but the analysis shown in Figure 2 suggests that this might not have occurred if the signal had not been influenced by a thermoelectric signal or shock perturbation at the electrode. The ends of the signals in Figures 4 and 5 could be equally misleading, especially with a long risetime.

The initial portion of a signal, such as shown in Figure 3, may make it difficult to identify the time of shock entry into the dielectric. The signal components in Figures 3 and 7 are identical, but the risetimes differ by a factor of two. This results in approximately a factor-of-two change in the amplitude of the initial portion of the signal. Consequently, the initial rise (or dip) may be prominent with a short risetime, but inconspicuous and possibly lost in background noise when the risetime is long. This is the explanation presently advanced to account for variations in the initial portion of polyethylene signals from similar experiments. This explanation may also account for observations reported in reference [3], where in similar impact experiments on sodium chloride, a small negative dip was sometimes present at the beginning of signals (see Figure 1-B) and sometimes missing.

VI. SUMMARY AND DISCUSSION

A shock-induced electrical signal from polyethylene at 47 kbar has been analyzed within the framework of the Allison polarization theory and resolved into positive and negative components which add algebraically to provide reasonable overall agreement with the observed signal. This lends support to the contention that this theory may be applicable even though the observed signal suggests an anomaly upon first inspection. Noting the similarity between

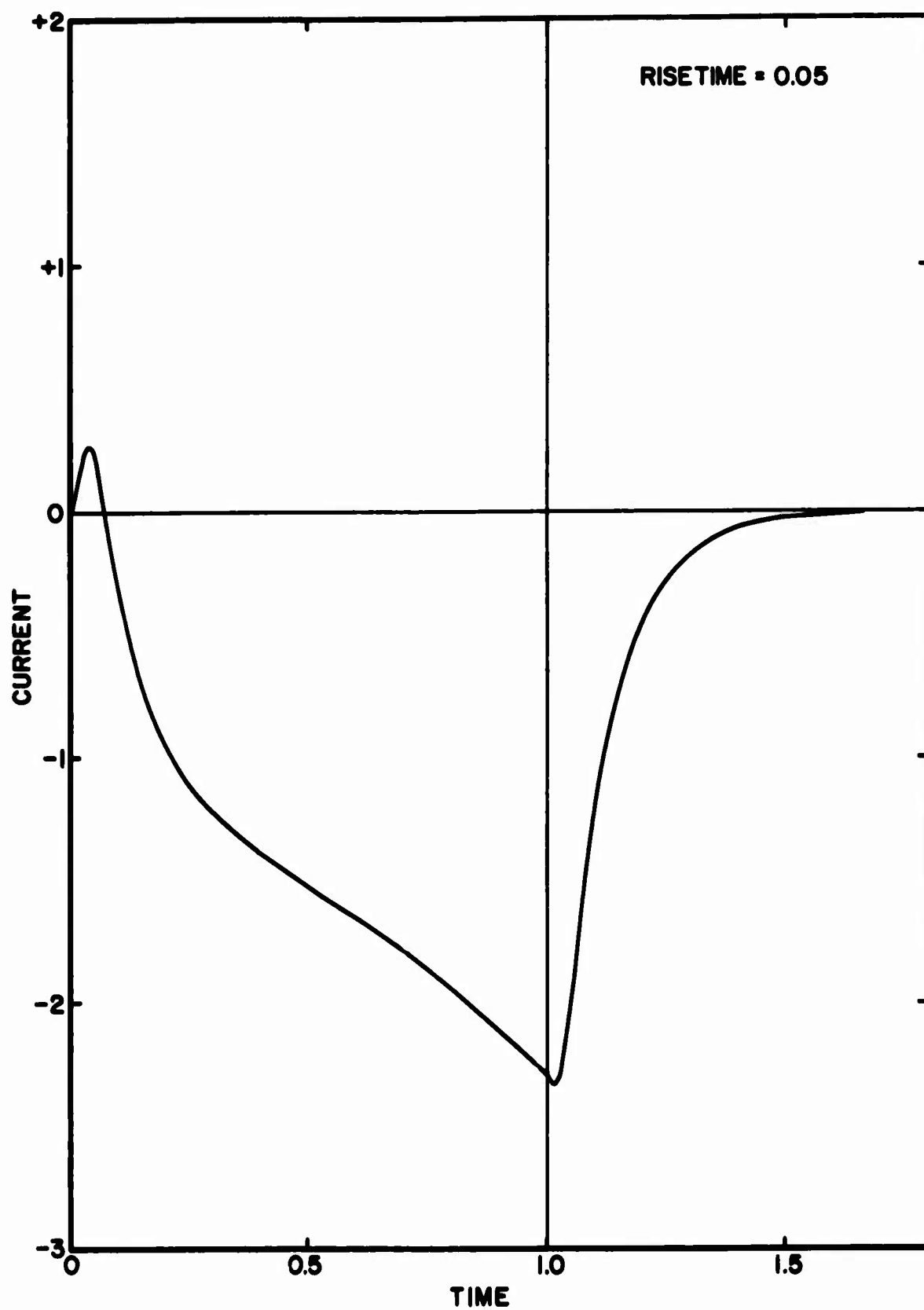


Figure 7. Two-component signal with components identical to those of Figure 3, but with risetime reduced to show the influence on the amplitude of the initial positive portion.

polyethylene signals and certain alkali halide signals, the Allison theory has been used to calculate two-component hypothetical signals which qualitatively display the basic features of a few alkali halide signals selected from the literature. Although the two-component signals are undoubtedly an oversimplification, they do suggest the general nature of the positive and negative components that should be present. A quantitative interpretation of alkali halide signals will require carefully designed experiments in which both the polarization and relaxation portions of the signals are studied, and the analysis would most certainly benefit from independent information about the effect of shock compression on the dielectric constant. In the study of shock-induced electrical effects in dielectrics, the resolution of complex signals into components seems a necessary step toward understanding the nature of shock wave interactions with a dielectric structure.

When both positive and negative components are present and the signal risetime is finite, the polyethylene signal and the hypothetical signals suggest that features of the signal profile may not clearly indicate the times of shock wave entry and emergence. Although problems may not be encountered, potential sources of error exist, and polarization signals with positive and negative components should be used cautiously for the evaluation of shock-wave transit time.

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